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Emergence of Marine Fishery Advisory services and their impact on achieving sustainable fisheries in India: A review

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Abstract

Sustainable fisheries development is increasingly critical amid rising global demand for marine resources. In this context, the Indian Marine Fishery Advisories, particularly Potential Fishing Zone (PFZ) and Ocean State Forecast (OSF) Advisories, have emerged as key tools to enhance fishery practices while reducing uncertainty and risks. The Earth System Science Organization-Indian National Centre for Ocean Information Services, under the Ministry of Earth Sciences, has been providing satellite-based PFZ and OSF Advisories since 1999 and 2009, respectively. PFZ Advisories guide fishers to areas of high fish aggregation, whereas OSF services enhance safety through accurate ocean weather forecasts. These advisories are disseminated daily to the coastal fishing community across India through multiple channels. Despite demonstrable improvements in catch per unit effort and fisher incomes in many regions, significant disparities remain in access and utilization of these services. Public–private partnerships, particularly those involving non-profit organizations, have the potential to bridge these gaps by improving outreach and community capacity-building at the grassroots level. In addition, international experience shows that co-management practices can support long-term sustainability in fisheries. This study reviews the dissemination and utilization of PFZ and OSF Advisories globally, with a focus on India, and evaluates their socioeconomic and environmental impacts. It identifies barriers to access, highlights successful models, and explores future needs for inclusive and sustainable fishery development. The findings aim to inform policy frameworks that align with the Sustainable Development Goals, particularly those related to poverty reduction, food security, and marine resource sustainability.

Keywords: Potential fishing zones; Ocean state forecast; Indian National Centre for Ocean Information Services; Marine Fishery Advisory; Dissemination; Sustainable fisheries; Catch per unit effort; Sustainable Development Goals 14

1. Introduction

The fisheries and aquaculture sectors have been treated as the "sunrise sector" in India.[1] The fishery sector in India can be characterized by small-scale farming, employs over 16 million people, and doubles in the value chain.[1,2] During the 11th 5-Year Plan, the output value of growth from the fishery sector was about 3.6% annually, where ₹24.83 billion was allocated for the fishery sector.[3] The fish production in India has since been increased by almost 17-fold, from 0.75 million metric tons (Mt) in 1950–1951 to 13.42 Mt in 2018–2019.[2] In general, India as the second largest fish producer country in the world after China, accounted for 6.56% of global fish production during 2017–2018.[4] Fishery sector has contributed for 5.23% to the Agricultural Gross Value Added (GVA) and 1.07% to the country's GVA during financial year (FY) 2017–2018 (Figure 1A), which is about ₹1755.73 billion.[2] India also earned a significant amount of foreign exchange worth ₹465.89 billion (US$6.73 billion) from fishery export, which is 5% of the overall export and 19.23% of the total agricultural export.[2] Along with the utilization of 8118 km long coastline consisting of 0.53 million km^2 continental shelf area within 2.02 million km^2 of exclusive economic zone (EEZ) in India, the estimated total annual harvestable marine fishery potential was about 5.31 Mt whereas 3.71 Mt (approximately 71%) has been harnessed across its nine maritime states, two union territories, and two island territories (Figure 2) during FY 2018–2019.[2,3,5,6]

According to the Food and Agriculture Organization of the United Nations (FAO), total global marine fish production was about 108 Mt in 2016, where India contributes about 3.65%.[4] Currently, fish provides 16% of the total global protein[7]; however, India only accounts for 28% of the marine fish production (3.71 Mt) of the total production of 13.42 Mt.[2] India stands in sixth position in global marine fish production after China, Indonesia, USA, Russia, and Peru, which contributed about 4.5% to the total global production.[4] According to the report prepared by the Marine Products Export Development Authority, the marine fish production in India has increased from 0.53 Mt in 1950 to 3.71 Mt in 2018 (Figure 1B). However, marine fish capture from the Indian mainland declined by 9% in 2018 compared to 2017.[8] The maritime state of Gujarat, located in the north-west of the Indian coast, remained the largest producer of marine fish (approximately 0.72 Mt) in the country. At the same time, maximum species diversity (735 species) was contributed by Tamil Nadu and Kerala.[8] India exported 1.38 Mt of seafood (worth US$7.08 billion) during 2017–2018 compared to 1.13 Mt (worth US$5.78 billion) during 2016–2017, with an annual growth rate of 21.35% in terms of quantity, where Frozen Shrimp (41.10% of overall export) was the major exported item.[6] Countries, such as the USA, along with Southeast Asia and Europe, are the major importers of these seafoods. According to the decade report prepared by the Department of Agricultural Research and Education–Indian Council of Agricultural Research,[8] the composition of commercially important fish species in India has decreased dramatically in recent years due to the changes in environmental parameters, such as water quality and salinity.

Monitoring of fishing activities in the deep ocean is required for better fisheries management as well as to conserve marine biodiversity.[9] Although fish productivity is limitless and it is a renewable resource, overexploitation due to high demand, along with global warming and climate change, renders this sector critical, which becomes a major threat to the livelihoods of the coastal community.[10] The continuous exposure to salt water, sand, and frequent natural calamities, such as cyclones and storm surges, increases the vulnerability of their livelihoods in India.[11,12] Bottom trawling, overcapacity of the fishing boat, and continuation of the government subsidies for the mechanized fishing crafts are the main

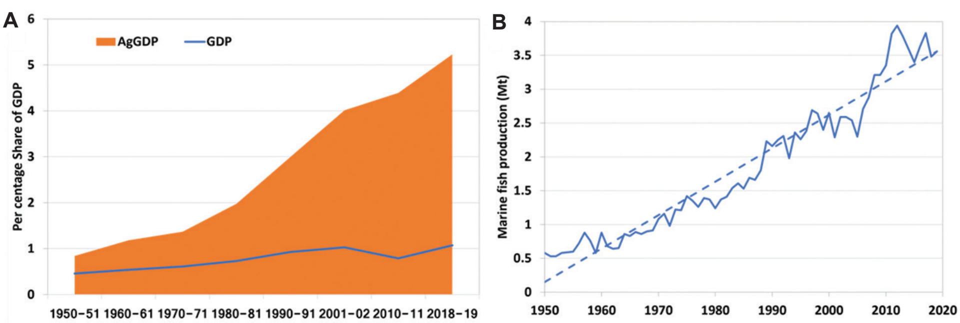

Figure 1. Trends in marine fish landings and economic contributions over the past decades. (A) The change in marine fish landings over the past decades. (B) Contribution to the total GDP and agricultural GDP from the fisheries sector in India over the past decades. Image created by the author.
Abbreviations: AgGDP: Agricultural gross domestic product; GDP: Gross domestic product.

Figure 2. The location of nine maritime states, two union territories, and two island territories contributed to the marine fish production in India. Image created by the author.

reasons behind the overexploitation of the marine fish, resulting in severe damage to some species, requiring preservation.[13] Adequate resource management (Figure 3) for sustainable utilization of marine resources needs to be strategized under current scenarios.[14] Empirically, fishing populations used traditional indicators of ocean features, such as temperature and color "breaks," feeding birds, foam, and accumulation of floating objects, to locate fish aggregation zones in the open sea.[15] However, the locating and catching of the marine fish became challenging due to the decline in the fish stocks in the usually available locations, which can be recovered by a reliable and timely forecast on the fish aggregation using remotely sensed data.[16] In this connection, remote sensing technology is being used for sustainable fisheries management by locating fish schools in the open sea more prominently and also for monitoring the ocean environment.[17-19] To avoid tremendous pressure in the traditional fishing zones due to increasing fishing fleets, several fishing effort needs to be diverted to the suitable potential fishing zone (PFZ) of the open sea.[20] Remote sensing technology can identify PFZ based on various satellite-derived products, such as sea surface temperature (SST) and chlorophyll concentrations (CC), where fish are available. Therefore, remote sensing techniques can play a huge role in marine resource exploitation (mainly fish) with the lower effective cost by saving fuel as well as search time, which also reduces the burning of fossil fuels.[15] Due to the sustainable use of marine fishery resources, the regulation related to fisheries must be implemented through scientific Marine Fishery Advisories (MFAs) based on satellite data.[21] To reduce the uncertainty and risk during the fishing operation, remotely sensed MFAs have high potential. Historically, the USA first started fish predicting zone using remotely sensed data in 1971.[22,23] To reduce the unpredictable weather patterns and non-availability of fish in the usually available location, the Indian National Centre for Ocean Information Services (INCOIS) had started to provide PFZ Advisory in the late 1990s on behalf of the Government of India.[24] PFZ, a short-term and reliable forecast on the fish aggregation zone in the open sea, helps fishers to locate large fish shoals through the reduction in search time and saves fuel.[17,25] The increasing demand for marine fishery products was also a major reason behind the adaptation of PFZ Advisory in India.[25] In the case of India, presently, marine fishing practices have been concentrated within the narrow belt of 50 m depth in inshore water.[26] INCOIS has also started the ocean state forecast (OSF) service in 2009, which includes wave heights, wave direction, wind speed and wind direction, tides, and currents to ensure the safety of the fishermen during fishing. OSF is also helpful as a decision-making tool for venturing into the deep ocean, and is also useful for the other coastal communities during extreme events.[27,28]

The current review provides a detailed mechanism of the INCOIS-derived MFAs along with their evolution throughout the periods. Besides, the usefulness and benefits of the MFAs are discussed across various maritime states in India through reviewing various literature. Therefore,

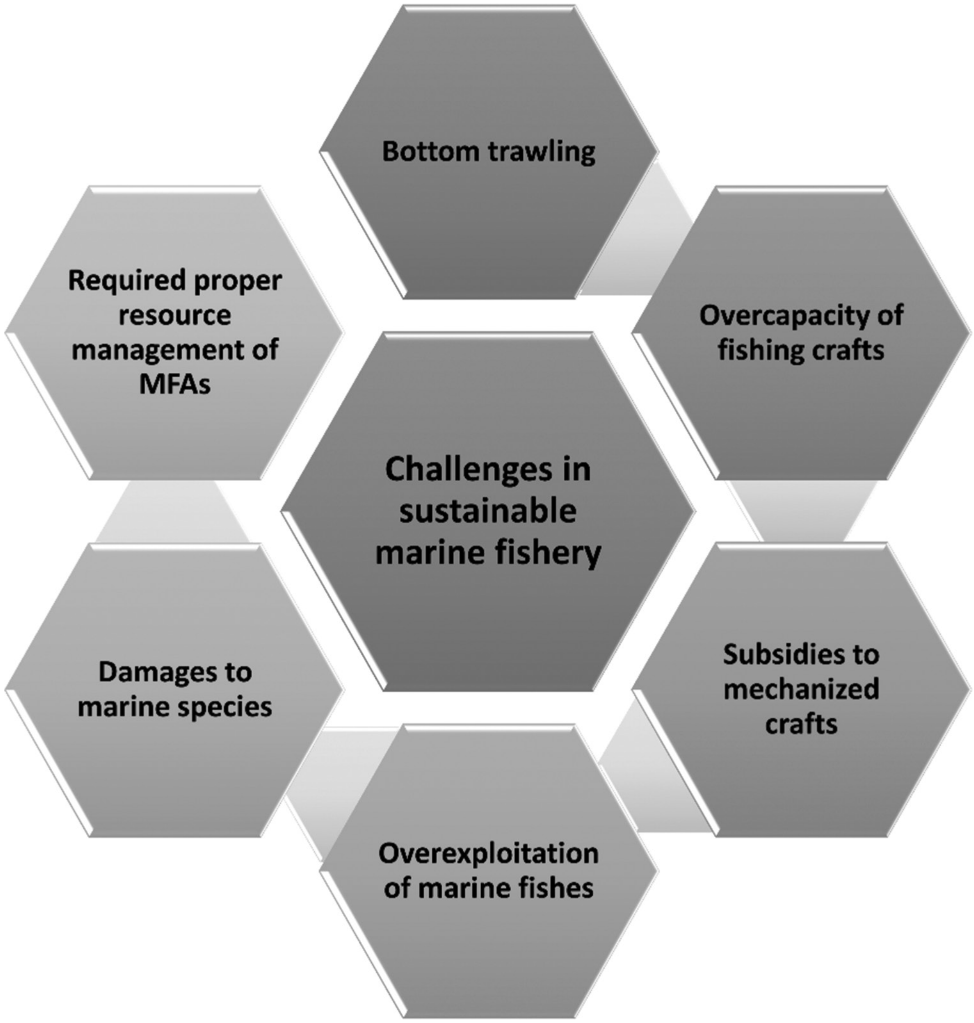

Figure 3. Challenges and managerial problems in the marine fishery sector in India and scope through the use of Marine Fishery Advisories (MFAs), such as the Potential Fishing Zone and Ocean State Forecast. Image created by the author.

the present review is significant for understanding the overall scenario of the development, dissemination, and impacts of advisories in the Indian context. Moreover, a global overview of the MFA has also been discussed. Furthermore, the role of MFAs in achieving various Sustainable Development Goals (SDGs) imposed by the United Nations through sustainable fishery practices was reviewed. These will also be helpful to understand the futuristic scope to improve the same with respect to its development and dissemination, as well as usages to enhance the sustainable fisheries in India.

2. Materials and methods

The literature reviewed in this article was identified through targeted searches in several scientific databases, including Web of Science, Scopus, and Google Scholar, covering publications between 1984 and 2025. Keywords used in various combinations included: "Marine Fishery Advisory," "Ocean State Forecast," "Dissemination," "CPUE," and "SDG 14," depending on the specific focus of each subsection.

Publications were selected based on their relevance to the topic and their contribution to the understanding of various criteria. For example, biological control of invasive alien plant species, physio-biological processes behind fish abundance, development and dissemination of PFZ Advisories, influence on the fish capture, socioeconomic benefits of PFZ and OSF Advisories, and methodological robustness. Preference was given to peer-reviewed journal articles, although relevant books, reports, and gray literature were also considered where appropriate. No strict inclusion/exclusion criteria were applied, as this is a narrative review aiming to provide a broad overview of the current knowledge and emerging trends in the field.

3. Development of MFAs in India

3.1. Physio-biological processes in the ocean and fish abundance

The static nature of the marine ecosystem controls the distribution of fish, whereas the oceanographic conditions, such as SST and CC, that indicate the fish stocks,[17,29] can be traced by utilizing the remotely sensed data.[30] The presence of phytoplankton containing high CC indicates high primary productivity regions where the marine fishes concentrate due to the presence of food.[23] Therefore, the ocean color (high CC) provides the area of rich biological products, which are also related to the oceanic fronts, topographic structure, upwelling, and eddies, known as fish accumulation zones for their feeding and spawning.[31-33] On the other hand, SST can be characterized by a suitable environment in terms of temperature for enhancing biological productivity.[34] For instance, cool water contains the highest nutrient materials, and therefore, SST is inversely correlated with PFZ areas.[32,34] The studies conducted by Solanki *et al.*[35] and Kripa *et al.*[36] also found that the temperature gradient in the ocean attracts fish, whereas the ocean color features coincided with the thermal fronts associated with the high primary productivity. In this context, special oceanic processes (SOPs), such as upwelling zones, the location and evolution of frontal boundaries, and current eddies, are also significant in the case of marine fisheries habitat.[37] For instance, cyclonic eddies found with high CC lead to high fish catch, whereas the anti-cyclonic eddies are associated with low fish catch due to the absence of high CC.[30] Therefore, the presence of chlorophyll (Chl) along with favorable SST is highly favorable for the fish aggregation in the open ocean, as illustrated in Figure 4.[23]

The behavior of fish is influenced by the favorable ocean environment, including seawater temperature, salinity, pH, and dissolved oxygen (DO), as each fish species has their own favored water temperature range, prey availability (near fronts), water clarity (turbidity), and productivity zones (ocean color) for their survival.[14,17,20,27] Marine pelagic fishes usually aggregate with a sharp horizontal temperature gradient up to a depth of 50 m in the ocean.[38,39] Seawater temperature and its seasonal and interannual fluctuation are the most important environmental parameters to find out the relationship between the behavior of fish and their abundance in the ocean environment.[15] It has been recorded that the optimum temperature for cold water fishes ranges between 20°C and 28°C, whereas warm water fishes can survive above 28°C.[22] On the other hand, CC >0.2 mg/m^3 in the sea is favorable for commercial fishery.[40] Furthermore, DO, an important water quality parameter required for acquiring the living organism, is inversely correlated with the water temperature,[41] while sea surface salinity (SSS) determines the density of seawater.[9] It is interesting to note that more fishing spots are found during the winter season; however, fishers need to travel farther offshore and spend more time at sea to reach deeper fishing areas compared to the summer season.[42] For example, organized tuna fishing is conducted at the submarine ridge of the Lakshadweep region, consisting of low seasonal variability in terms of different seawater parameters, such as salinity and turbidity, due to the distance from the mainland.[43] Tuna fish is also highly sensitive to temperature.[31] Due to the wind direction and wind movement, the oceanic features, such as eddies, rings, and fronts, are found to be shifted. This water mass movement due to the wind is also closely associated with the dispersal of fish shoals.[44] To understand the probable shift, Hossain *et al.*[29] incorporated the wind speed and wind direction data in the PFZ map.

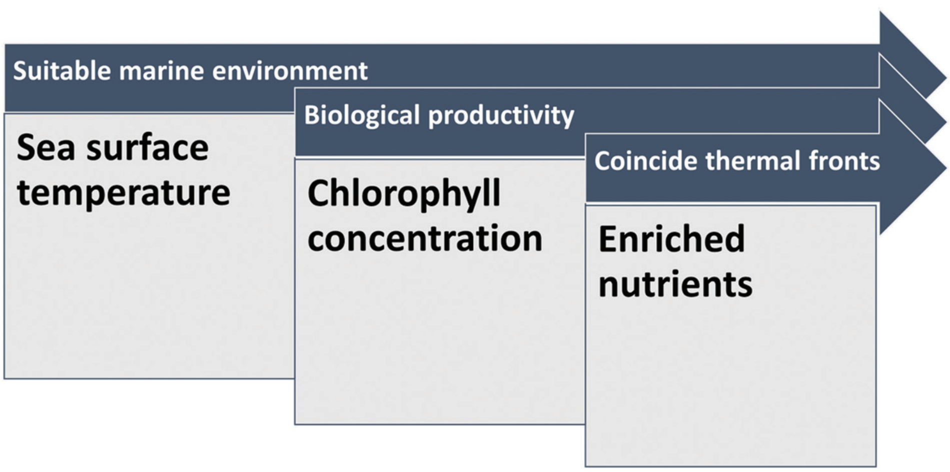

Figure 4. Key physio-biological processes influencing fish abundance in the ocean, forming the scientific basis for Marine Fishery Advisories. Image created by the author.

3.2. Background and evolution of MFAs

Historically, the USA started a fish-prediction zone in 1971 worldwide for the first time using remotely sensed data. To understand the relationship between Chl and SST, Arnone[45] used coastal zone color scanner and National Oceanographic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA–AVHRR) data, whereas Laurs *et al.*[46] found that tuna fish are distributed in the vicinity of fronts where water is relatively warmer, utilizing these datasets. In the case of India, MFAs in the form of PFZ forecast had been developed during 1989–1990 for the first time using NOAA–AVHRR derived SST at Space Application Centre (SAC), Ahmedabad.[37] Meanwhile, the National Remote Sensing Agency was the institutional body for PFZ Advisory generation and dissemination. By developing "merged SST," incorporating the buoy temperature, wind observations (diurnal variation correction) with the AVHRR-extracted SST, Karthikeyan[47] stated that SST will also be useful to locate cold-blooded fish in the ocean. Tingote and Mane[48] also found that the environmental parameter called SST can easily be correlated with the availability of pelagic fish. However, SST-derived PFZ Advisory was inadequate in tropical and equatorial waters during summer due to strong stratification, preventing the arrival of cool nutrient-rich waters to the sea surface from the deeper layer, and surface wind might also affect the frontal structure.[49] Later, SAC developed an integrated approach using satellite-derived CC and SST to locate PFZ in the Indian seawater, and it was handed over to the Earth System Science Organization (ESSO)-INCOIS in late 2001 after the successful launching of the Indian Remote Sensing Satellite-P4 (IRS-P4) Ocean Colour Monitor (OCM) on May 26, 1999.[50] For the experimental PFZ forecast, an integrated approach had been developed by Solanki *et al.*,[35] where CC was calculated through atmospheric corrected OCM data utilizing Ocean Chlorophyll-2 algorithm and SST was estimated through multichannel SST approach as suggested by McClain *et al.*[51] Solanki *et al.*[52] also did a synergistic analysis of Sea-WiFS derived CC and NOAA–AVHRR derived SST for fishery resources exploration and observed an inter-relationship between CC and SST. Later, Solanki *et al.*[53] had analyzed Chl data from IRS-P4 OCM and SST data from NOAA–AVHRR to generate a composite image (using both Chl and SST) by monitoring common oceanic features, as the thermal features represented by coincident CC and SST contours indicated high bio-physical processes in the ocean. Recently, Mane and Mishra[37] also stated that integrated CC and SST are also able to identify SOPs, namely frontal boundaries, upwelling zones, current eddies, and meander, in the tropical ocean where fish accumulate due to the favorable environmental conditions along the temperature boundary. Therefore, the integration of SST with CC is more effective for PFZ forecast, as fish such as to congregate along the temperature boundary enriched with biological productivity.[26] INCOIS used both the approach where composite images were generated using common frontal structures using SST and Chl data, along with the second approach, the usage of the Chl data alone.[49]

3.3. Identification and visualization of PFZs utilizing remotely sensed data

The fish shoals can be located according to their feeding grounds from the combined SST/Chl image generation through the detection of various oceanic features.[54,55] The Chl features coincide with the temperature boundaries, indicating the maximum physio-biological processes in the open sea, which are useful for the exploration of living marine resources.[31] IRS-P4 OCM-derived CC and NOAA–AVHRR-derived SST data (Table 1) are transferred onto a scaled base map through the ground control points from the SOPs to generate the integrated PFZ map.[14,56,57] Therefore, the matching features from both Chl and SST in the SOPs are crucial to identify the PFZ map. To understand the probable shift of the PFZ area, wind vectors had been overlaid on the color-coded Chl/SST combined images after the geometrical correction. In this connection, wind data derived from Seasat-A Satellite Scatterometer

Table 1. Details of the datasets, along with the respective satellite name and agencies used to generate the PFZ Advisory

Basic input of PFZ Advisory	Details of the satellite		
	Satellite name	Respective agency	Remarks
SST	NOAA–AVHRR	NASA, USA	Retrieved from thermal-infrared channels of the respective satellites
	Met-Op	EUMETSAT, ESA	
Chl	Oceansat-II	ISRO, India	Retrieved from the optical bands of the respective satellites
	MODIS Aqua	NASA, USA	

Abbreviations: Chl: Chlorophyll; ESA: European Space Agency; EUMETSAT: European Organization for the Exploitation of Meteorological Satellites; ISRO: Indian Space Research Organization; Met-Op: Meteorological Operational Satellite; MODIS: Moderate Resolution Imaging Spectroradiometer (onboard Aqua satellite); NASA: National Aeronautics and Space Administration; NOAA–AVHRR: National Oceanic and Atmospheric Administration–Advanced Very High-Resolution Radiometer; PFZ: Potential fishing zone; SST: Sea surface temperature; USA: United States of America.

had also been tested for improved results.[56] Solanki *et al.*[44] developed an algorithm to compute the shifting nature of ocean features and the water mass movement due to the wind circulation, utilizing QuikSCAT from the National Aeronautics and Space Administration (NASA)-derived SeaWinds data. To understand the effect of wind on the PFZ Advisory, Chandran *et al.*[31] had also used wind data obtained from QuikSCAT Scatterometer. Therefore, due to the proven linkage between SST and Chl for the fish aggregation zone, the PFZ line/curves can be delineated by understanding the SOPs due to their high biological productivity.[16,36] Using the superimposed PFZ map from 2003 to 2007, Kripa *et al.*[36] also observed that the 50 m depth in the nearshore region over the southeastern Arabian Sea is more persistent for fish abundance due to high river water discharge containing high nutrients.

In the case of India, the PFZ Advisory began under the MFA services of INCOIS, imposed by the Government of India, and was closely associated with locating pelagic fish. According to the report prepared by Swetha *et al.*[58] on behalf of ESSO-INCOIS, the vector traced from one image was initially superimposed on another image to delineate the PFZ map (Figure 5), which was time-consuming and highly prone to manual error. Thereafter, the method associated with the automated identification of the frontal zone was implemented, reducing the human-induced error and also shortening the operational process chain. For example, single-image edge detection-derived output was considerably modified through polyline vector and cloud masking, where the ArcGIS toolbox, such as "Spatial Analyst" and "Cartography," was utilized to make smooth line curvature. Using this geospatial approach, the detection time of thermal fronts within the EEZ was shortened by 10–15 min. Later in 2011, ESSO-INCOIS initiated the generation of PFZ Advisory using SST and Chl from multiple satellites, which became completely automated in 2013.[50] Over 2008–2017, ESSO-INCOIS also developed the Satellite Coastal and Oceanographic Research program to overcome the difficulties in generating PFZ Advisory during cloudy days, especially during the monsoon, which is the peak fishing period, and also to encourage the fishing personnel to restrict themself only to pelagic fishing practices in the deep ocean.[50] Therefore, INCOIS used both the approach where composite images were made using common frontal structures using SST and Chl data, along with the second approach, the usage

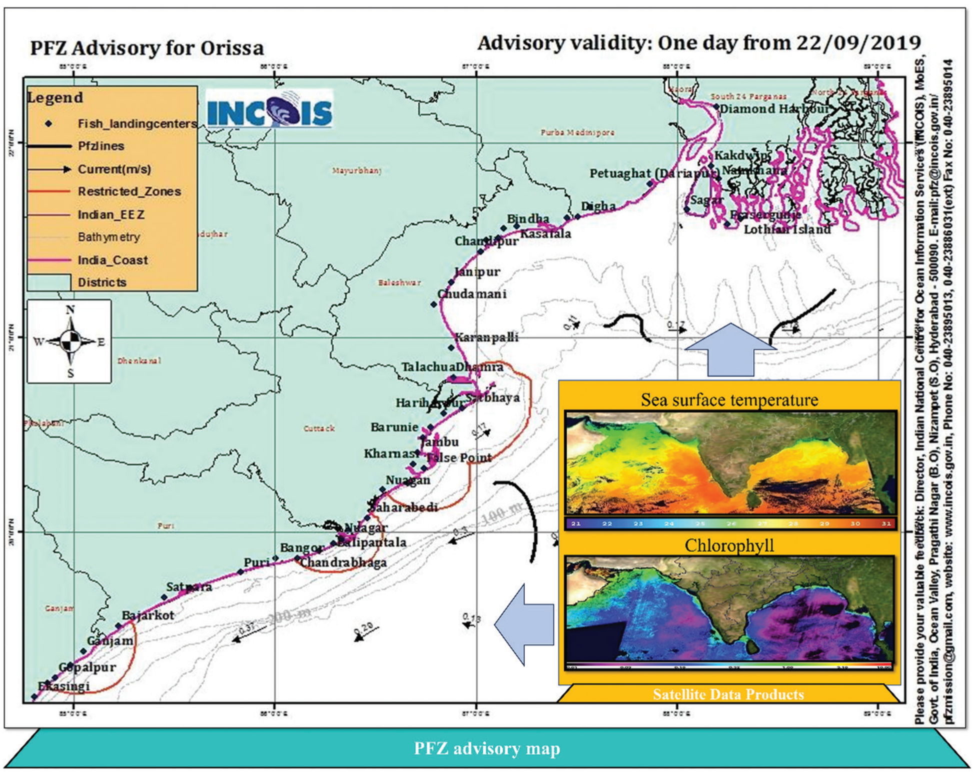

Figure 5. Visualization of basic primary input. The sea surface temperature and chlorophyll of the PFZ Advisory (inset panel) and a sample of the PFZ Advisory for Odisha for September 22, 2019. (Source: INCOIS web portal, weblink: https://incois.gov.in/MarineFisheries/PfzWebGis).
Abbreviations: INCOIS: Indian National Centre for Ocean Information Services; PFZ: Potential fishing zone.

of the Chl data alone.[49] The feedback analysis over the Indian West Coast during 1999–2001 also indicated that the SST-Chl-integrated approach was 70–90% reliable and can increase the catch by up to 200%, whereas the SST-based approach was only 50% reliable.[55] In another study conducted by Solanki *et al.*[33] revealed that the catch per unit effort (CPUE) in the matching features (SST and Chl) was extremely high; 85% of the observations reported higher fish catch compared to other areas.

Though SST and Chl are used in India to develop and deliver PFZ Advisory, Balaguru *et al.*[59] reported that net primary production estimated from the vertically generalized production model using photosynthetically available radiation and Chl can also be treated as a key parameter to assess fish stock in the open sea. This is because the presence of high nutrients in the cool water is a suitable region for higher fish catch. Giri *et al.*[23] have developed a local spatial model to detect PFZ by generating line density using satellite-derived SST and Chl over the West Bengal Coast, and identified several highly probable fish catch zones, which were very close to the INCOIS-derived Advisory. Andrews *et al.*[60] enhanced the precision of PFZ using the support vector machine (SVM) mechanism, which can be predictive in the absence of satellite data, thereby reducing time wastage and making the process cost-effective. However, Natteshana and Kumar[61] found that a statistical model is more efficient in identifying PFZ using the rough clustering techniques compared to an SVM classifier. To improve the existing remote sensing technology for identifying PFZs using satellite-derived SST and Chl data in Ratnagarh District, Maharashtra, Mane and Mishra[37] utilized the R tool, achieving an accuracy level of up to 89% within the predicted area. After calculating the SST (20–25°C) and Chl (0.10–0.22 mg/m^3), the values were combined with the X and Y coordinates to obtain the SST and Chl matrix, which was used to delineate the PFZ region utilizing the R tool. Mudliar *et al.*[9] developed a machine learning model to identify the PFZ in the open sea using water quality parameters, including DO and SSS, through an autoregressive integrated moving average and a random forest model. Furthermore, Chakraborty *et al.*[50] have developed a model to reproduce PFZ with high confidence, transforming PFZ Advisories into PFZ forecasts using model-derived Chl and SST, even on cloudy days, for sustainable and effective marine fisheries. Satellite altimetry data can also be utilized to provide pelagic fish advisories throughout the year by avoiding the unavailability of satellite data on cloudy days.[62] Altimetry-derived sea surface height anomaly (SSHa) and eddy kinetic energy data have been analyzed and compared with optical satellite products to obtain PFZ Advisories even on cloudy days.[59] This study revealed that the usage of optical sensor data along with altimetry (multi-sensor data) is very useful to identify the PFZ, as well as species-specific PFZ. Solanki *et al.*[63] also carried out an integrative analysis of the CC, SST, and Satellite with Argos and Altika-derived SSHa for better fisheries application, where it has been found that satellite-derived low SST and low SSHa designate high CC. Therefore, negative SSHa regions are characterized by rich nutrients, enhanced phytoplankton growth, and increased biological productivity, attracting fish shoals. However, an ocean-color sensor can penetrate into the ocean water up to 10 m, and can represent more frontal structures, which are true biological fronts. Currently, active remote sensing instruments, such as radar and sonar, are utilized in the field of marine fisheries.

4. Dissemination processes and managerial practices of MFAs

Indian INCOIS provides the PFZ and OSF Advisories for the marine fishing community to all the fish landing centers across the country, except during the fish ban period imposed by the Government of India.[24,38,64] Utilizing satellite data on SST, Chl, water clarity, and SSHa, INCOIS provided PFZ service for the 299 days during FY 2018–2019, along with 290 days of Yellowfin Tuna Advisory.[65] The advisories related to the PFZ and OSF are being disseminated to the various fishing villages/fish landing centers along the entire Indian coast through various information and communication (ICT) based tools, *viz.* digital display systems (DDSs), e-mails, phone calls, text messages, audio messages, radios, fisheries helpline numbers, mobile applications, local television networks, newspapers, community networks, and distributions of forecast printouts in person (Figure 6) to the targeted fishermen.[24,62] The PFZ forecast has also been sent via e-mail to various companies and agencies, including the Agromet Field Unit, All India Radio, and local functionaries of the Department of Fisheries (DOF), for radio and newspaper transmission, where it is challenging to obtain feedback on this process. In some states, such as Tamil Nadu, INCOIS collaborated with several non-profit organizations (NGOs), including the M. S. Swaminathan Research Foundation (MSSRF) and Reliance Foundation Information Services (RFIS), for local-level dissemination.[24] In this context, MSSRF acts as a catalyst by raising awareness through village resource centers (VRC) and village knowledge centers (VKC) in Tamil Nadu and Puducherry.[66] MSSRF has also conducted several awareness campaigns across 29 districts of Odisha, Andhra Pradesh, Puducherry, Tamil Nadu, and Kerala, reaching over 90,000 fishing population.[67] According to the market study report conducted by MSSRF[68] in collaboration with INCOIS, it was reported that some fishers in the coastal villages of TN and PND were unable to utilize PFZs

Figure 6. Different information and communication-based dissemination processes of the potential fishing zone and Ocean State Forecast Advisories in India. Image created by the author.

Abbreviations: DDS: Digital display system; EDB: Electronic display board; FFMA: Fisherman-friendly mobile application; SMS: Short message service; VKC: Village knowledge center; VRC: Village resource center.

as the forecasted zones were located far away from their traditional fishing ground, and they came on an irregular basis. There was also a demand for species-specific PFZs for Tuna (already started), Mackerel, Carangids, Oil Sardines, Seer-fish, *etc*. The fisherfolk population also expected additional training for the effective utilization of the PFZ and OSF Advisory. The study conducted by the National Council of Applied Economic Research (NCAER)[66] also concluded that greater emphasis needs to be placed on the dissemination processes of the PFZ and OSF services at the grassroots level. In this context, the INCOIS–MSSRF partnership could be a milestone in this sector for the purpose of smooth dissemination through the "Fisher Friends Programme." Kumar *et al.*[38] also noted that an awareness enhancement program may be helpful for the smooth dissemination of these advisories and increase economic benefits in terms of reduction in search time, fuel saving, and enhancement in CPUE.

The new generation electronic display boards (EDBs), known as DDSs, were inaugurated by INCOIS in January 2018. A total of 66 DDSs were installed along with 72 existing EDBs as of March 31, 2018.[28] The problems of the usage of the electronic board in the PFZ dissemination are the requirement of electricity, maintenance, and the skill to operate.[69] Currently, INCOIS has installed 98 DDSs along India's coastal regions, in addition to 85 existing EDBs. During 2018–2019, the total number of registered users of MFAs at INCOIS reached nearly 9 lakhs (approximately 900,000).[65] *The DDS* also has the capability to reduce the strains of different hazards by disseminating the real-time ocean state, namely wave heights, wind speed, and wind direction, and tsunami warnings along with PFZ Advisory.[62] However, the effective utilization of DDS was hampered due to limited installation, prevalence of poor GPRS, lack of local expertise to address the issues in DDS units, and the issues related to the power supply at the installed sites. ICT-based EDB/DDS consists of two parts: a liquid crystal display and a secure siren system. It also has two components: a table and a map.[25] Along with the possible fish aggregation zones in dark line (known as PFZ), the map also provides the probable shifting location of fish, depending on the wind speed and wind direction. The texts contain details of direction, distance, depth, latitude, and longitude, along with the global positioning system location of fish aggregation zones.[25] For better usage of PFZ, it is advised to catch fish on the same day after receiving it. Fishing in the middle of the PFZ line, inside the curved area, and between two PFZ lines yields maximum catch. The shifting features of the PFZ line indicate the movement of the fish shoal for the next two days.[25] Therefore, the fishing operation became more useful when it was undertaken on or closer to the dates when the related SST/Chl data were received from the satellite.[38]

The information and forecast on different oceanographic parameters, namely waves, tides, currents, SST, and mixed layer depth (MLD), are being provided on a daily basis under the OSF Advisory; the frequency of dissemination generally increases during extreme weather conditions for the people who venture into the sea, and also for the near-seashore people.[28] According to the study of Chrispin *et al.*[70], a positive correlation was found between awareness/usage of PFZ and OSF Advisories and the level of education, where the utilization of the PFZ Advisory is negatively correlated with the usage types of crafts, namely mechanized and motorized crafts, in the state of Tamil Nadu. Furthermore, the study revealed that government organizations, such as the DOF, are less effective but more sustainable, while NGOs are more effective but less sustainable in the case of INCOIS-derived advisory dissemination at the grassroots level. It was concluded that effective public–private participation (PPP) is necessary for community participation and the utilization of ICT-based tools to further strengthen the dissemination processes at the grassroots level.[70]

5. Impacts of MFAs

According to various studies conducted by different agencies,[66-68,71,72] it has been noted that the CPUE increased due to the use of PFZ and OSF Advisories (Figure 7). In addition to enhancing fish catch, PFZ Advisory is useful in reducing search time, thereby decreasing fuel consumption, making marine fishing more environmentally friendly by emitting less carbon dioxide. On the other hand, OSF Advisory is very helpful in making the decision to venture into the sea and can save the lives and livelihoods of fishers, as well as those of coastal communities. Regarding the usage of advisories, various socio-technical constraints were identified among marine fishers, along with their socioeconomic factors, which influenced the dissemination and utilization of MFAs in Odisha. It is also noted that fishers agreed about the fruitfulness of the advisories if these could be used regularly.[73,74]

5.1. Influence on the fish catch

To investigate the effectiveness of PFZ Advisory in India, most studies have focused on two widely used methods: CPUE and benefit–cost ratio (BCR). The formula used for the CPUE is shown in Equation (1).

$$\text{CPUE} = \frac{\text{Total weight of fish catch}}{\text{Fishing effort}} \quad (1)$$

Typically, CPUE is expressed in kg/h, where the total weight of fish caught is measured in kg and the fishing effort is expressed in hours. High CPUE represents the most favorable oceanographic conditions for fishing operations.[20] Chrispin *et al.*[70] studied the CPUE within the PFZ notified area, which is significantly higher than that in the non-notified area, saving 50% of fuel and reducing search time along the Maharashtra coast. The study conducted by Solanki *et al.*[33] concluded that species-wise CPUE and seasonal CPUE were also found to be higher in the PFZ-notified area compared to the non-notified area along the Gujarat coast from 1999 to 2002.

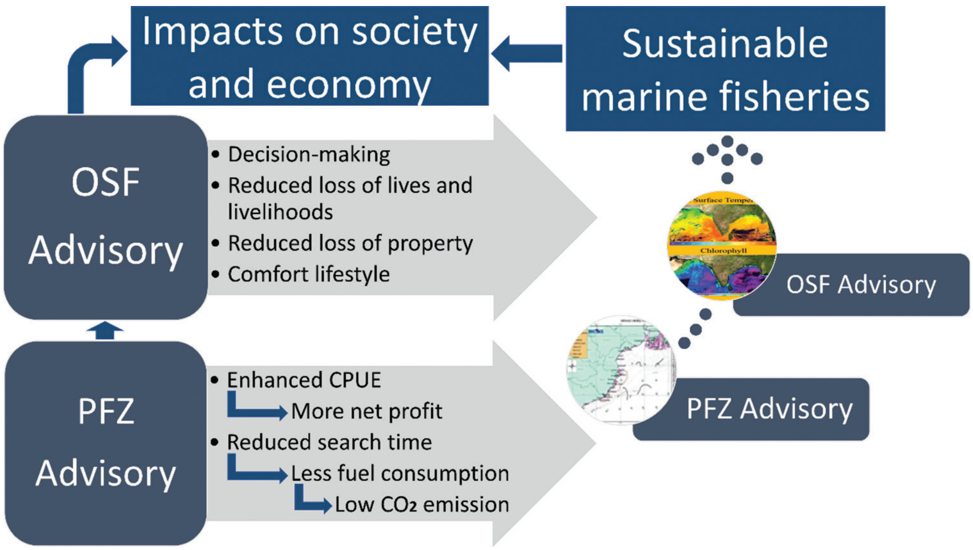

Figure 7. Impacts of PFZ and OSF on marine fisheries for the sustainable fishery to achieve socioeconomic improvement in India. Image created by the author. Abbreviations: CPUE: Catch per unit effort; OSF: Ocean State Forecast; PFZ: Potential fishing zone.

On the other hand, BCR compares the total expenditure of each trip against the total benefit of each trip, also known as cost-benefit analysis.[75] To compute the BCR, Nayak *et al.*[54] considered the cost toward the forecast generation, expenditure toward fishing, and profits from the increased catch, summarizing BCR by the total returns against total cost (Equation [2]).

$$BCR = \frac{\text{Total returns}}{\text{Total cost}} \quad (2)$$

The feedback received from various studies conducted in different regions of India since 2001 to validate the PFZ Advisory is presented in Table 2.

To locate pelagic fish in the open sea, the PFZ Advisory generated from satellite-derived SST and CC can reduce the overall operating costs of fishing.[80] This remote sensing technique is more suitable for pelagic fish compared to demersal fish, as light cannot penetrate deeper water.[33,79] Furthermore, Tummala *et al.*[14] also concluded that the success rate of the PFZ Advisory is about 85% for the bottom trawling and 95% for the gillnetting, which can be improved by incorporating parameters such as MLD and wind. In

Table 2. Economic improvement in marine fisheries through the use of the Potential Fishing Zone Advisory compared to non-potential fishing zone areas at various spatio-temporal scales in India

No.	Location on the Indian coast	Year	Crafts and gears used	Total catch or yield	Status of CPUE	Status of net profit	Status of BCR	References
1	Gujarat	2001			Two- to three-fold increased			Solanki *et al.*[35]
2	Lakshadweep	2002		55 kg increased	Three-fold increased			Pillai *et al.*[43]
3	Western coast	2003 and 2005	Trawler and gillnet			₹26,887 (trawler) and ₹1299 (gillnet) increased	0.85 (trawler) and 0.84 (gillnet) increased	Nayak *et al.*[54] Dwivedi *et al.*[55]
4	East coast	2002–2004	Trawler, gillnet, and longliner	Increased by 36.50±1.97 kg/h, 33.82±2.42 kg/h, and 30.41±3.58 kg/h for gillnetters, trawlers, and long liners				Choudhury *et al.*[57]
5	Kerala	2006–2008		2671 kg increased	4.3-fold increased	₹54,423 increased		Tummala *et al.*[14]
6	Gujarat	2010		0.99 tonnes increased	1.3-fold increased	₹99,202 increased		Das *et al.*[76]
7	Kerala	2003–2011						Nair and Pillai[27]
8	West Bengal	2008–2011		Increased by 51.47±4.30 kg/h	Two-fold increased		4.5 increased	Maity *et al.*[75]
9	West Bengal	2008–2011		Increased by 17.48 kg/h	Two-fold increased			Dutta *et al.*[21]
10	East coast	2010–2012		Increased by 4.64 kg/h	2.32-fold increased			Dutta *et al.*[21]
11	Tamil Nadu	2007–2011		Increased by 45 to 1070 kg	8.64-fold increased	₹4300 to ₹36,000 increased		Nammalwar *et al.*[26]
12	Andaman and Nicobar Islands	2009–2012	Gillnet, trawler, and longliner	Percentage increased by 36.50±1.97, 33.82±2.42, and 30.41±3.58, respectively				George *et al.*[77]
13	Goa			Increased by 1.06 tonnes/h		Six times increased		Sreekanth *et al.*[78]
14	Mumbai	2014		Increased by 12 kg/h				Kamei *et al.*[22]
15	Goa			Increased by 2405.1 kg/h	2.35-fold increased	1.86 lakhs increased	1.69 increased	Sreekanth *et al.*[79]
16	Gujarat						0.08 increased	Nayak *et al.*[16]

Abbreviations: BCR: Benefit–cost ratio; CPUE: Catch per unit effort.

most cases, the trawl operation of PFZ Advisory is more beneficial at 50 m depth.[70] According to different studies, it can be said that the net profit obtained by the fisherfolk population, as well as the species diversity, was higher in the PFZ region compared to the non-PFZ region.[61] Dutta *et al.*[21] also found that the differences in total catch and profit were statistically significant at a 5% level of significance on the West Bengal coast. According to the validation of the satellite-based PFZ Advisory along the Kerala coast during 2003–2011, Nair and Pillai[27] exhibited that the CPUE and net profit earned by the fishing community were higher within the PFZ notified area compared to outside the PFZ. There was also a positive correlation between PFZ and the occurrence of commercially important pelagic fishes. However, the abundance of fish decreased when the forecast gap increased.

The validation of PFZ Advisory reveals that motorized and small mechanized crafts are the primary beneficiaries, with a forecast reliability of up to 80%.[16] Hossain *et al.*[29] also concluded that catch is higher in the PFZ area compared to other areas, beneficial for the artisanal, motorized, and small mechanized crafts engaged in pelagic fishing. In another study conducted by Dutta *et al.*,[21] the total CPUE in West Bengal has declined due to the increase in mechanized boats and over-exploitation of fish. The INCOIS technical report prepared by Kumar *et al.*[38] concluded that PFZ Advisory is beneficial for fishing by reducing search time and, consequently, reducing fuel consumption. They also studied that commercially important fish species are abundant in the PFZ area compared to the non-PFZ area. Sreekanth *et al.*[78] utilized 304 feedbacks based on 136 PFZ Advisories to compute CPUE and net profit along the Goa Coast, where the searching time was also reduced by 50% due to the usage of PFZ Advisory. The study conducted by Nammalwar *et al.*[26] also concluded that the PFZ forecast by INCOIS using remotely sensed data was highly useful for fishing, as it can enhance the CPUE by minimizing search time and thereby saving fuel and human effort, resulting in an overall profit for the fisherfolk population.[39] It not only saves fuel by reducing search time but also makes their livelihood more reliable by increasing income and preventing them from venturing into the sea in adverse weather conditions as a result of the OSF Advisory.[24] Masuluri *et al.*[81] found that PFZ Advisory is useful and effective to reduce the environmental stress by decreasing the carbon dioxide (CO_2) emission in the open sea; the average CO_2 emission reduced by 0.8 tonnes in the PFZ region (0.161 tonnes) compared to the non-PFZ region (0.959 tonnes) along the Kerala Coast from 2008 to 2011. Therefore, the comparative study of CPUE drastically varied between PFZ and non-PFZ locations. High yielding (CPUE) can also boost the economic status of small-scale fishing communities. It is crucial to note that the emergence of COVID-19 and its associated lockdowns in various phases significantly impacted the marine fishery sector in India.[82]

5.2. Socioeconomic benefits of PFZ and OSF Advisories

The socioeconomic status of the fishing population depends on assets, such as fishing craft and gear. Traditional catamarans (dinghies) represent the poor fishers, whereas motorized or mechanized craft holders are comparatively rich.[83] The fishing gears, including types of nets and lines, influence the socioeconomic status of the fishing population. The majority of the Indian population (65%) relies on the agricultural sector to pursue their livelihoods, where the fishery sector is also an important component.[84] The renewable nature of marine fish in the fishery sector plays an important role in the socioeconomic development in India for the following factors: increasing food security, sharing a significant amount of foreign exchange, and generating employment.[71] Therefore, the Union Government of India focused on the high fish productivity to ensure the socioeconomic security of the artisanal fishermen by means of the sustainability of the marine fisheries. In general, fisheries come under the state subject as per Article 246. However, fishing beyond the territorial waters is a subject of the central government.[10]

The National Council of Applied Economic Research was appointed by the Ministry of Earth Sciences (MoES) in 2010 to conduct a comprehensive study to estimate the economic and social benefits due to the weather and marine services, such as agro-meteorological advisory services, fishery services, tsunami warning services, severe weather warning services, and public weather forecast services. According to the study of NCAER,[66] where a total of 400 respondents were selected for impact assessment of the marine fishery services from five villages across four districts (Kalyani, Guntur, Nagapattanam, and Puducherry) of corresponding four states (West Bengal, Andhra Pradesh, Tamil Nadu, and Puducherry), PFZ and OSF, provided by INCOIS were found quite useful among the fishing community. Identification of PFZ improves the catch size by increasing fish productivity. It also reduces fuel consumption by minimizing search times. On the other hand, information regarding ocean state (OSF) is useful for the fishing population/general public in timing departures and arranging shore activities by avoiding extreme weather events in coastal zones.[66] This study also claimed that the adaptation of PFZ Advisory for all mechanized, motorized, and traditional crafts can contribute up to 2.04% of the national gross domestic product (GDP). The total annual net economic benefits due to the satellite-based PFZ Advisory were estimated within the range of ₹34,000 to ₹50,000 crore based on the export of approximately 21% additional catch due to the usage of PFZ Advisory. NCAER[66] reported that 90% of fishers in the southern coastal region and 64% in the eastern region are aware of the usefulness of the ocean state services. In 2015, another study was conducted by RFIS–NCAER to assess the economic benefits, along with the environmental and ecological benefits, of INCOIS-derived PFZ and OSF Advisories in the coastal villages of seven maritime states in India. According to NCAER,[71] marine fisheries GDP can increase up to 7.8% from the current 3.9% after the uniform operationalization of PFZ and OSF Advisories across all the coastal regions of the country. Due to the usage of PFZ and OSF forecasts, fishers can also obtain an additional profit of ₹3000 crore per annum. Identification of PFZ also minimizes search time, resulting in a reduction in diesel consumption. Saving one liter of diesel can reduce 2.63 kg of CO_2 emissions and ₹36,200 crores per annum over a 25-year life. Due to the greater accuracy of PFZ and OSF, the fishers can improve their health and spend quality time with their family members, as their manual work in the crafts will decrease significantly; accuracy in the PFZ may also reform a new ecosystem, which can be treated as its ecological benefit.[71] Furthermore, the study conducted by Kundu and Santhanam[85] reported that 2.20 lakh tonnes of CO_2 emission can be reduced due to the usage of PFZ Advisories in Odisha.

Apart from NCAER studies, INCOIS also conducted several market studies from 2012 to 2013 to assess the impacts of PFZ and OSF Advisories on improving the lives and livelihoods of the marine fishing communities in different parts of the country, especially across the coastal villages of Andhra Pradesh, Tamil Nadu, and Puducherry. The MSSRF collaboration with INCOIS since 2009 bridges the gap between scientific know-how and ground-level do-how in the coastal districts of Tamil Nadu and Puducherry, disseminating the PFZ and OSF Advisories through VKC and VRC.[68] The market study conducted by MSSRF[68] among 300 individuals from the fisherfolk population across six coastal districts of Tamil Nadu and Puducherry revealed that 94% of the total fisherfolk utilize either PFZ or OSF Advisories through the text messages of their mobile phones. The total net income for all the fisherfolk has increased by at least ₹1000 to ₹50,000, along with the reduction of several issues regarding overfishing due to the usage of PFZ Advisory, while oil sardines were the most dominant species caught. OSF includes wind speed and direction, and wave heights are closely related to the effective decision-making of fisherfolk for fishing; a timely forecast can prevent economic loss by avoiding natural hazards at the ocean. The majority (35%) of the fisherfolk agreed that due to the usage of OSF, they can attain net economic savings of ₹5000 to ₹20,000.[68] According to another market study conducted by MSSRF[67] among 32 fishers, including a woman boat owner in the Gilakaladindi Village of Krishna District (Andhra Pradesh), reveals that the usage of PFZ improved the quality and quantity of catch. For instance, the yield of tuna fishing has increased from 200–300 kg to 400–500 kg per haul. The number of days spent in the ocean was also reduced from 10-15 days to 4-5 days, thereby reducing diesel consumption, a major economic gain of nearly ₹25,000 per trip. Therefore, the income of the boat owners and crew members (drivers and laborers) has increased significantly. The study conducted by Tummala *et al.*[14] along the Kerala Coast over 2006–2008 revealed that the search time was reduced by 50% within the PFZ region, indicating an annual saving on the diesel consumption (6 lakhs for mechanized crafts and 1.80 lakhs for motorized crafts). To locate pelagic fishes in the open sea, the PFZ Advisory generated from satellite-derived SST and CC reduced the overall operating costs of the fishing.[80] Therefore, it can be concluded that the benefits of PFZ-OSF Advisories are useful for time saving (reducing the time of the trip), fuel saving (decreasing CO_2 emission and pollution), as well as increasing catch (more income) and producing safety among the fishing population. The doctoral research conducted by Kundu[86] investigated the development and dissemination processes of MFAs in detail for Odisha. It was found that the assimilation of the MFAs usage was hampered in this state due to various socio-technical constraints, as only 30% of the total fishers utilized this advisory during the study. However, significant environmental and economic benefits were achieved through MFAs. It was reported that the emission of 2.20 lakh tonnes of CO_2 could be reduced per year using MFAs, while 45% of daily expenditure for fishing can be reduced through its regular utilization, which enables climate-resilient fishing in Odisha. A recent study by Santhanam *et al.*[87] also revealed that MFAs are crucial for reducing emissions to achieve the optimal social cost of carbon in India.

It is well-documented that climate change poses significant threats to marine fisheries by altering ocean temperatures, currents, productivity, and species distribution, which in turn undermine the sustainability of fish stocks and the livelihoods of coastal communities that rely on them. Singh[69] reported that SST can be increased over the Indian coast by 2.0 to 3.5°C by 2099 from the current level of 0.2 to 0.3°C (1960 to 2005). Two major concerns of the marine fisheries in India are the decline in fish catch and the increase in fuel prices.[69] Therefore, better fisheries management is needed in the near future to maximize the utilization of living marine resources, such as fish, through a deep understanding of marine ecology. Apart from fishery management, such as monitoring the environment and locating fish populations, ocean color is also used to monitor harmful algal blooms, as well as to locate coastal populations.[49] It is evident from the present analysis that the utilization of MFAs not only benefits fishers economically by increasing their catch but also reduces search time, thereby decreasing fuel consumption and resulting in lower CO_2 emissions to the marine environment. Therefore, this adaptive strategy not only enhances economic efficiency but also promotes ecosystem-based sustainable fishing practices, thereby strengthening the resilience of fisheries and fishing communities to climate variability and long-term climate change.

6. Global overview of the Marine Fishery Advisory

The nature of MoES's advisories related to PFZ and OSF is a public good in the Indian context. The PFZ and OSF Advisories are disseminated to all the coastal fishing community freely (non-excludable), and the utilization of these advisories by a fisherman cannot affect the others (non-rival), as anybody can venture into the sea to fish in the PFZ areas.[88] On the other hand, the marine fishery resources are treated as a common public property, which is non-excludable but not non-rival.[88] The common property problems caused by a lack of property rights in the fisheries resources create problems such as economic inefficiency. In this context, the individual transferable quotas (ITQs) can be adopted to establish property rights in the fishery sector, thereby minimizing the economic inefficiencies. Despite the dynamic nature of the fishery, ITQ can bring sustainable economic benefits, leading to an increase in economic efficiency. This is implemented in Iceland along with the Netherlands, New Zealand, and Australia.[89] Community-based coastal resource management systems can also be treated as an active social process by involving resource users—the local fishers and communities—as partnership management in the resource management.[90] According to the international experience, fisheries co-management, a decentralized system of marine resource management where user participation is involved, needs momentum to get its solid motion; however, decentralization does not necessarily mean participatory management or co-management always.[91] The community participation and ownership collaboration with the municipal government play a creative role in the usage of a financial mechanism for a long-term, self-supporting marine protected area in the Philippines.[92] For instance, in the San Salvador Island, Philippines, the community and local government contrasted with the National Marine Park based on the Marine Protected Area to pursue better management under the National Integrated Protected Areas. Pinkerton[93] examined the potential of the community-based self-management and government-community co-management to clarify the biological, economic, and political problems regarding the salmon fishery in British Columbia and Canada. According to Pomeroy,[94] three key elements were identified to understand the achievements of locally based regimes: logistical, cost-sharing, and power-sharing elements. Logistical arrangements included clear boundaries, membership criteria, interception agreements, and management-unit sizes appropriate to the abundance of the natural and human resources; cost-sharing arrangements include local cost recovery and local volunteerism; and power-sharing arrangements include checks and balances between local multiparty boards, a provincial board, and the Department of Fisheries and Oceans. The primary goal of the co-management program is to mobilize and strengthen public participation in government, as well as to ensure the equal distribution of resources and powers among local-level people and communities.[94] In fishery practices, cooperation and participation of fishers are needed to develop laws and regulations for the fishing population.[90] To minimize the resource management problems related to resource deterioration (Philippines and the Tanzanian marine), conflicts between stakeholders (e.g., Norway's Lofoten cod fishery and Philippines coastal fisheries), conflicts between management agencies and local fishers (e.g., Canada's Atlantic coast fishery), and governance problems in general (e.g., Philippines, United States Fishery), the fisheries co-management had been adopted globally.[94]

After World War II, world fisheries had been increasing steadily. In developing countries, fish have been treated as the primary source of animal protein, as they consume 70% of the total fish landings. Despite the Third United Nations Conference on the Law of the Sea, the fishing pattern has not changed significantly. However, the developing countries produced the largest catch, accounting for nearly 80% of the total world catch.[95] The estimations of several hydrological factors, such as the upwelling zone, along with high primary productivities that attract fish shoals for their food, are needed to assess marine fish.[17,96] Mansor *et al.*[97] realized that it is urgent to develop a model suitable for the PFZ determination in tropical water to meet the sustainable harvest of the fisheries resources. Based on the satellite-derived SST and CC, a fishery forecasting model, the Tropical Fish Forecasting System, was developed to provide PFZ Advisory to end-users in the South China Sea. Klemas[17] reported that SST (NOAA–AVHRR), CC (SeaWiFS/SeaStar), along with SSHa (Ocean Topography Experiment/Poseidon) and wind velocity (Scatterometer/European Remote Sensing Satellite-1 and -2) were helpful to trace out the abundance of yellowfin tuna in the tropical Atlantic region. Apart from this, commonly used acoustic sensing methods, such as echo-sounders (used for deep fishing) and side-scan sonars (used for near-surface fishing), can provide high-resolution data on fish distribution and abundance from the trawler itself. The Ocean Acoustic Waveguide Remote Sensing method is also a useful technique for continuously monitoring fish population behaviors, dynamics, and abundance on the continental shelf. In the case of airborne remote sensing, the spatial resolution/coverage, along with a cloud-free environment, low altitude (tidal) conditions can be chosen easily. Therefore, airborne Lidar can overcome the limitations of passive remote sensing, while side-looking airborne radar can track fish shoals by accumulating small-scale waves (2–20 cm) resulting from fish swimming activity. Active microwave devices, such as radar altimeters, scatterometers, and synthetic aperture radar, are being used to detect physical ocean features. Despite limited spatial resolution (effective only for open seas) and inability to penetrate cloud cover (due to its polar orbit), the Moderate Resolution Imaging Spectroradiometer is attractive as it can produce both CC and SST.[17] Pillai and Nair[39] also mentioned that satellite-derived SST and CC are ideal for providing high receptivity and large spatial coverage for monitoring the ocean. Dimech *et al.*[98] reported a negative correlation between the perception of fishers over the Malta fishing zone and the fishing activity. The fishing zone was not beneficial for commercial fishers, whereas recreational fishers were the main beneficiaries. They also found that the differences in individual incomes among the fishing population lead to attitudinal differences, which enhance the resources, as well as the conflicts among user groups.

In the case of India, the fisheries sector needs a proper management system for food security, similar to the White Revolution, in the near future.[99] Currently, the annual average fish production by Indian fish farmers is 2 tonnes per person, whereas it is 172 tonnes per person in Norway. To increase the standard of living of the Indian fishing community, it is necessary to increase productivity and export marine fish at a higher intensity. In this context, the transfer of knowledge from the developed country is also very important for sustainable fishing.[80] It is also needed to raise awareness among the fishing community to stop illegal fishing, for example, through the use of double-fold nets.[47] The Central Marine Fisheries Research Institute had proposed to ban fishing during the breeding season, prohibit gears with a 30 mm mesh size, and restrict the export grade to 1400 Nos./kg and above by the fishers in the context of overexploitation.[13]

7. MFAs and sustainable fisheries

Hinds[95] projected that fisheries may be a major contributor to food security in the future by improving management strategies. There is an urgent need for collaboration among fisheries, industry, and remote sensing scientists to improve forecasting models and develop suitable management strategies.[17] In this context, SDG 14 provides the development targets with respect to marine resources management, which can be enhanced using PFZ and OSF Advisories, specifically in relation to regulating pelagic overfishing, conservation of marine fisheries, implementation of subsidies, and regulating the socio-economics.[100] It is noted that fishing utilizing the scientific MFAs is economically beneficial and environmentally sustainable due to higher fish catch in a shorter duration. The adopted 17 SDGs with 169 targets and 230 indicators under the "Agenda 2030" by the United Nations, SDG 14—Conserve and sustainably use the oceans, seas and marine resources for sustainable development—is one of these goals where FAO is the custodian agency. Apart from SDG 14 (Life Below Water), small-scale fisheries (SSF) can be related to SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 5 (Gender Equality), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 16 (Peace, Justice and Strong Institutions). According to the workshop proceedings, edited by Franz, FAO,[101] SSFs (including fishery resources, land, and market) are facing a wide number of challenges regarding lack of infrastructure, overfishing by big trawlers, pollution, habitat degradation, insufficient market information, post-harvest losses, weak organizations, and lack of access to financial services. Therefore, it is crucial to develop a reasonable, legal, and regulatory framework to achieve SDG 14, especially SDG14.b (Life Below Water). To serve this purpose, three variables: existing regulators, ongoing guidelines, and the existence mechanism in the field of SSFs have been prepared based on the FAO Code of Conduct for Responsible Fisheries. To serve this purpose, questionnaires can be prepared against these variables utilizing reliable methods at the national level to collect the information, which should include a multi-stakeholder, multi-disciplinary, and participatory approach based on a bottom-up approach. In this connection, a capacity-building program among the fisherfolk population may contribute to ensuring a robust reporting process. Based on the discussion made in this workshop, it is necessary to develop ICTs for disseminating the required methods through workshops, media campaigns, training, and social media to the target groups. It is also urgent to develop a database to evaluate the status of SSFs in developing nations, such as India, where exchanges of thoughts can take place at various levels among countries. Finally, participation of SSF organizations in various decision-making processes by following the SSF Guidelines may be useful in achieving the SDG 14 goal.[101] Therefore, fish production may become a useful tool against malnutrition to improve the socio-economics of the fishing community by playing an effective role in the co-management of fisheries.[10]

The major problem with remotely sensed data in the PFZ forecast is the time lag between SST and Chl observations.[22] Microwave radiometers are a better choice for measuring temperature than IR, as they can penetrate clouds.[15,80] Due to the limitation in temporal resolution of polar-orbiting satellites, INCOIS explored the possibility of utilizing SST data from Indian geostationary satellites INSAT-3D and INSAT-3DR.[28] INCOIS also tried to incorporate PPP in the process of PFZ identification for the ecosystem-based fishery advisory. For the continuation of Hilsa Shad Advisory, INCOIS initiated the establishment of a coastal laboratory facility at Digha in association with the West Bengal Fisheries Department.[65] INCOIS also planned for wind monitoring (from QuikSCAT), species-specific advisory, and location-based advisory.[16] Future development in the fishing operation will rely on the combined usage of visible, infrared, and microwave sensors, as well as the availability of satellite technology to everyone connected to this activity, including fishing personnel, fish-allied industrialists, and fishery scientists.[15] In this way, it is possible to overcome the limitations in the field of fishery advisories, including the lack of support for demersal fishing and the unavailability of satellite data during cloudy seasons. To reduce drawbacks, such as the lack of sufficient knowledge to understand and recognize the PFZ area and the lack of interest in upgrading mechanized crafts, the fishing communities need to follow a cooperative approach within their society.[48] In this context, INCOIS is also involved in conducting various awareness programs among the fish farmers across the country with the help of different NGOs, such as MSSRF. The species-specific advisories related to tuna are already operationalized by the INCOIS.

Therefore, it is understood that MFAs are useful for sustainable fishing practices in India. However, the assimilation of the advisories was hampered, which can be mitigated by improving the dissemination networks, as well as adopting an active remote sensing technique to provide MFAs seamlessly even in cases of adverse weather conditions. In short, MFAs increase resource dependability by improving catch efficiency, ensuring safety, reducing costs, and supporting sustainable resource use, collectively making marine fisheries a more reliable source of livelihood and food security.

8. Conclusion

The MFAs, developed and disseminated by ESSO-INCOIS under the MoES, the Government of India, play a vital role in the country's socioeconomic development related to the marine fishery sector through promoting sustainable fishing practices. Based on cloud-free satellite data, SST and CC are used to extract PFZ lines as fish shoals are found in suitable marine environments, such as those with relatively low SST and high CC. Several studies provided quantitative analysis regarding the benefits of fish catch from the usage of advisories, which is almost two to three times higher than fishing in non-PFZ areas in India. Advisories were also useful in decreasing carbon emissions due to reduced search time. Climate-resilient, sustainable fishing in attaining several targets of SDGs is achievable through the MFAs, as their use is economically beneficial for fishers and environmentally sustainable for the marine ecosystem. However, fishers reported that the PFZ Advisories they received were located far away from their traditional grounds, and the requirement for species-specific advisories was also noted. In addition, awareness programs associated with the reception and utilization of the advisories were identified as crucial for the fishers to use them. This would also help fishers to comply with regulatory guidelines related to illegal fishing or the use of inappropriate mesh sizes. On the other hand, PFZ Advisories are still not feasible during adverse weather conditions, which affect the continuity of receiving the same. In addition, the time lag between the dissemination of the advisory to the end-user and the fishing activity needs to be reduced for the effective use of MFAs. Advanced remote sensing techniques and fisheries co-management can play a vital role in reducing these drawbacks in the field of marine fisheries. This detailed review of the emergence of MFAs and their significance in sustainable fishing practices in the context of India may be useful for the marine research community in providing seamless next-generation advisories.

Under these circumstances, specific recommendations can be delivered as follows:

- Improving the transformational spaces for MFA deliveries by fostering participatory co-design, multichannel communication, localized content, and continuous feedback loops that enhance trust, accessibility, and adaptive use among fishing communities.
- Improving the focus or emphasis on transitioning to sustainable use of technologies for ensuring sustainable fishery development.
- Contextualization of specific SDG14 goals to specific tasks in MFA creation and delivery.

Furthermore, it is advisable to use the MFAs wherever feasible regularly, especially for mechanized crafts, as they can venture into the deep sea, unlike small motorized or non-motorized crafts for fishing, where PFZ Advisories are demarcated. Hence, this review is crucial to formulate required developmental plans for the marine fishing community so that fishers can receive and utilize PFZ and OSF Advisories seamlessly.

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